ULTRASONIC TECHNIQUES TO QUANTIFY MATERIAL DEGRADATION IN FRP COMPOSITES

Olajide D. Dokun, Laurence J. Jacobs and Rami M. Haj-Ali
Engineering Science and Mechanics Program
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta GA 30332-0355

INTRODUCTION

This is a progress report of research into use of ultrasonic waves to quantify the amount of damage in fiber reinforced polymeric (FRP) composites. The planned scope of the research involves three distinct stages of experimental work. First is the pre-damage stage when a baseline set of measurements on the composite material is taken. In this stage an effort is made to answer questions on issues like material variability, what range of frequencies can be propagated through it, or whether the material exhibits viscoelastic properties. Stage two, the damage stage, involves the introduction of damage into the material in an accelerated manner in order to simulate the effects of long periods of exposure to damaging environments. Damage mechanisms used are long term temperature aging, temperature aging in a water bath and bending fatigue. Optical imaging techniques will be used to verify that the damaging procedures have indeed produced a noticeable amount of damage in the matrix and fiber before we proceed to the next stage of experimentation. Stage three is the post-damage stage at which final measurements are taken. These final measurements must show a sufficient change from the stage one measurements above the known variability of the material for the imparted degradation change to be quantifiable. The report that follows here represents tests and measurements that are part of the stage one of the planned scope of work.

The E-glass reinforced, vinylester (thermosetting), pultruded composites in this research are primarily used in highway and other civil engineering applications. Unlike aerospace composites, these FRP composites are of relatively low quality, having much less uniformity of fiber distribution, and a much higher void content. This relatively low material quality, coupled with their thick cross-section (up to 25.4mm), necessitates the development of additional ultrasonic methodologies to interrogate these composites. This research will use both experimental and computational methods to study the effects of damage on the propagation of ultrasonic waves in FRP composites.
The experimental study uses the high fidelity and large bandwidth of laser ultrasonic techniques to measure frequency dependent attenuation. The computational model uses a commercially available finite element code, Abaqus, to model ultrasonic wave propagation in this material. A correlation will be developed between ultrasonic wave velocity, attenuation and the amount of degradation.

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THEORY

The fact that impedance mismatches at interface boundaries cause some of the energy to be reflected and the rest to be transmitted through complicate wave propagation in heterogeneous media like composites. This phenomenon known as scattering is affected by variables such as the relative values of impedance of the adjoining media, interphase geometry and the direction of incidence of a wave on the boundary. Scattering causes attenuation or loss of signal and thus it is more difficult to measure ultrasonic wave properties than in homogeneous media. Another factor affecting the propagation of waves is the extent of damping within a material. This damping leads to "absorption" or internal loss of the ultrasonic waves. In theory, as degradation increases in a composite, the damage thus introduced manifests in the form of fiber breakage, more and/or larger voids, matrix cracking and other forms of composite failure. These forms of damage all have in common the fact that they all lead to increased heterogeneity of the material and thus cause more scattering of waves. Attenuation changes in the material result from this increased heterogeneity. Attenuation is a measure of the amount of "loss" in a signal as it propagates through a material. There are three main mechanisms for attenuation loss: Geometric attenuation, Absorption attenuation and Scattering attenuation. Mathematically, Attenuation is defined by

$$W = Ae^{-\alpha x}e^{i(k.r-wt)}$$

Where W is the propagated wave and α is the attenuation factor. Experimental results are corrected for geometric attenuation to remove the effects of propagation distance. In the Rayleigh regime attenuation factor is expressed as

$$\alpha = af + bf^4d^3$$

Where
a = absorption coefficient
b = scattering coefficient
d = mean particle diameter
f = frequency

The linear term represents the absorption attenuation while the second is the scattering contribution. Other scattering regimes do not apply here since our length scales are within the Rayleigh regime.

EXPERIMENTS

Experimental work is done using laser based ultrasound. Laser generation presents us with a repeatable, broadband point source generation of ultrasound. Detection is through a heterodyne interferometer system that offers the advantage of being non-contact, high fidelity and broadband. The manufacturer's surface finish on the test sample was glossy enough to use the argon ion laser interferometer without the application of reflective tape. The Nd:YAG laser source had to be kept below a power level of about 6 mJ to prevent surface damage to the composite. For all experiments, the laser source was kept at 0.5mm diameter while the detection probe focused at 0.75mm[1].

[1] For this source and detection diameter combination the diffraction correction would be the 1/r. But this is a factor that will appear in both pre and post damage calculations and thus have no effect on the comparison of the two sets of measurements.

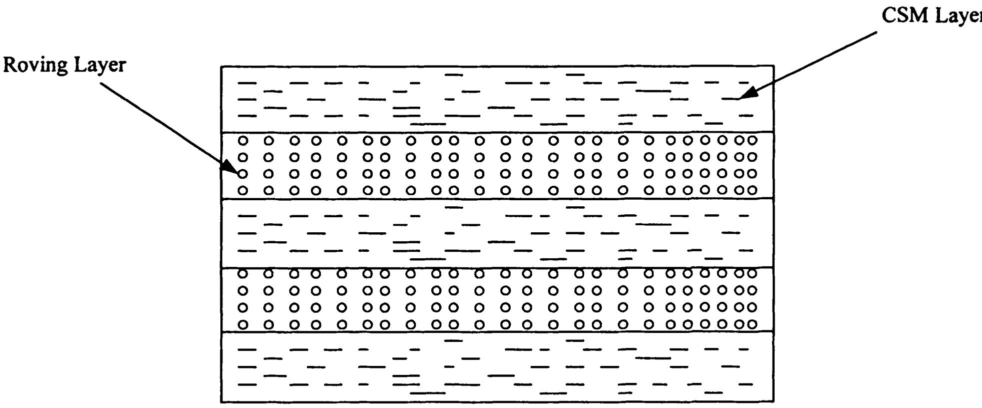

Figure 1. Representative 5 layer FRP Composite.

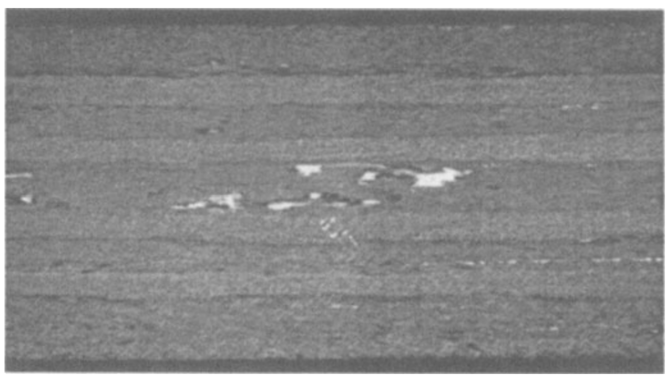

Figure 2. 10X photomicrograph of the cross section a 12.7mm thick FRP (white areas are voids).

The composite is composed of up to 9 alternate layers of Continuos Strand Mat (CSM) and roving material. Figure 1 shows a representative 5-layer FRP sample. The CSM layers have short strands of fiber randomly oriented in the plane of the layer. The Roving layers have straight long fibers that lay in the plane of the layers as well. The pultrusion manufacturing process is fast and low in cost but the end product have lots of voids that can be very large in size. Figure 2 shows a 10X micrograph of a 12.7mm thick cross section of a sample composite.

Due to high variation in the material, it is necessary that the same volume of material on the same specimen be used for all pre-damage as well as post-damage experiments. The material variation is such that the difference in measured quantities from different locations of the specimen may be higher than that due to the imparted degradation in the material at a specific location. Surface Rayleigh waves are selected for monitoring the change in wave amplitude attenuation with degradation change. The use of the Rayleigh wave was necessary for three reasons. Firstly, body wave reflections off the back of the material were too weak to be used for attenuation measurements. Secondly, the need to track the same volume of material precluded the use of specimens of different thicknesses to determine attenuation. Thirdly, the experiments had to be done

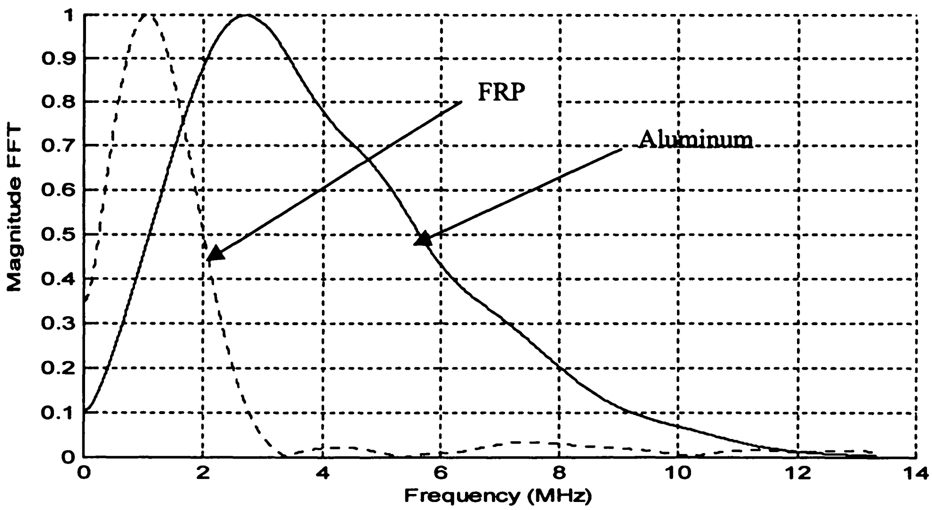

Figure 3a. Comparison of normalized frequency spectrum at 18mm from Source.

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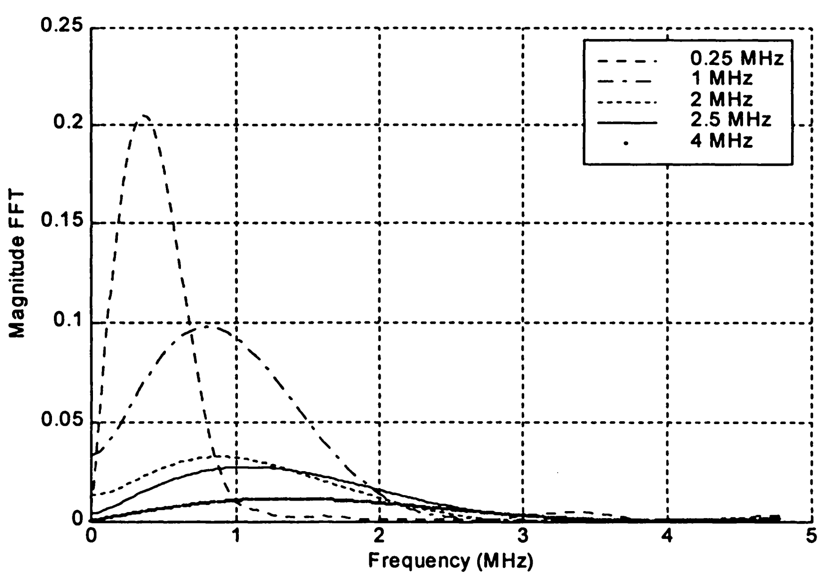

Figure 3b. Frequency spectrum in FRP at five different frequencies.

in the thermo-elastic[1] regime in order to prevent laser induced surface damage to the specimen. This resulted in relatively small signal amplitudes. Rayleigh waves with about 67 percent of the energy presented a consistently large enough SN ratio for attenuation measurements. With the single sided technique however we retain the ability to interrogate up to two times the wavelength in depth into the composite material. The Rayleigh waves interrogate up to two times their wavelength in depth into the composite material.

Preliminary results show that the material is highly absorbing with signals of above 3.5MHz frequencies being fully absorbed/scattered by the material. Detected signals show a shift in center frequency with increased distance from source and the Cutoff frequency also decreases with increased distance. All these suggest a very absorbing material. This is not surprising considering the polymeric content of the CSM and the Roving layer matrix. The polymer component of vinylester is known to show viscoelastic properties like material damping [2]. A demonstration of this FRP's absorbing nature is seen in Figure 3. Figure 3a shows the detected output signals from passing the same input into aluminum and the FRP composite specimen. Figure 3b shows a set of experiments done with piezoelectric transducers at discrete frequencies. The plots are of output signal's frequency content for the indicated input signal center frequencies. Pre-damage attenuation measurements were done using a multi-station method [3] that consists of a single fixed source and two detection probes. One probe is held at a constant distance from the source and is used for monitoring any source variation that may occur while the second is used to obtain measurements at several locations from the source. Attenuation calculated from the recorded signals in the undamaged material is plotted in figure 4.

COMPUTATIONAL

The accompanying computational effort to this research utilizes the Abaqus finite element software. A 2D plane strain model using 4-node rectangular elements with aspect ratio of one is used in none void location. This element selection is used to ensure an

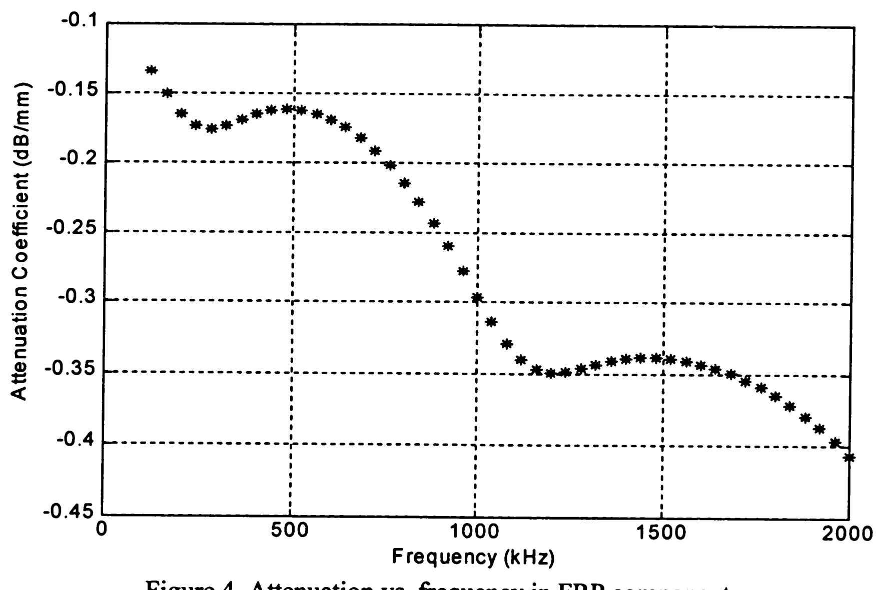

Figure 4. Attenuation vs. frequency in FRP component.

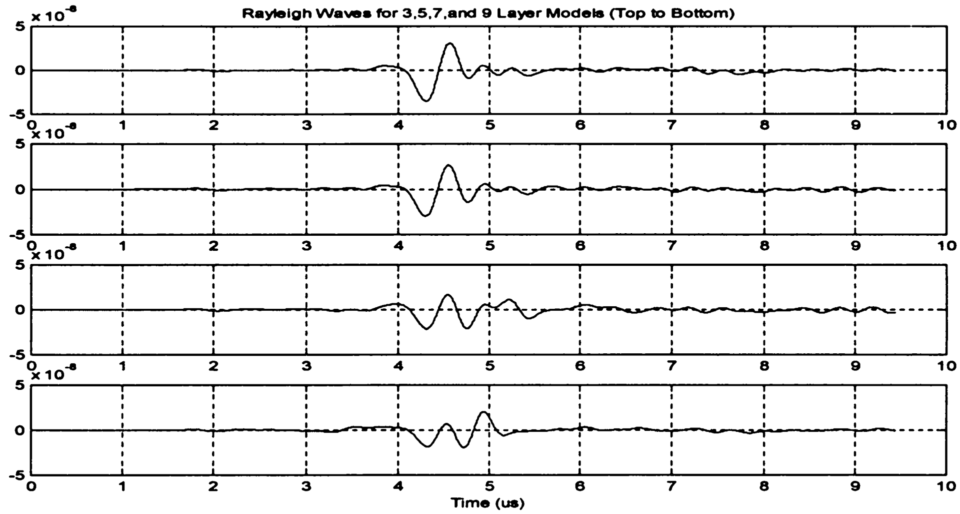

Figure 5. Computationally calculated Rayleigh waves in FRP of 3,5,7,and 9 Layer Models (Top to Bottom).

even distribution of mass in the mesh [4]. In the void boundary regions triangular elements are included. The explicit transient dynamics solution method is chosen due to its speed of execution despite its conditional stability [5]. The input point source was broadband with a cutoff frequency of 5MHz and center frequency of 2.5MHz. The model is meshed to a temporal and spatial resolution for propagation of waves of up to 5MHz frequency. A time step of 0.01 microsecond, one-twentieth of the center frequency is used while the mesh size was set at 0.06mm or one twentieth of the wavelength to be propagated. The composite is modeled using an equivalent modulus macro-mechanical formulation. The CSM layers are modeled as planar isotropic while the roving layers are modeled as orthotropic. Voids, modeled as holes, in the mesh were randomly distributed into the mesh.

Preliminary results with this model show arrival times that are consistent with theoretically predicted values. Absorption attenuation is variable through the use of the damping factor. The signal amplitude and waveforms were observed to change with increasing detection distance from source in this layered model. Also observed was that both amplitude and waveform of the Rayleigh wave is dependent on the number and size of the layers modeled Figure 5 shows the waveform changes observed for different number of layers of composite for the same total thickness.

ACKNOWLEDGEMENTS

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